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Water utilization characteristics of typical vegetation in the rocky mountain area of Beijing, China

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ABSTRACT

Seasonal drought are expected to occur more frequent and intense in the some regions due to global climate change, which may significantly influence in the competitive interactions of water uptake depth for vegetation communities. We investigated the impacts of seasonal drought on water utilization for vegetation communities using hydrogen-2 and oxygen-18 stable isotope techniques in Beijing rocky mountainous area. Our results indicate that the water sources of the four plant species varied by season. *Platycladus orientalis* largely absorbed water from middle (31.5% in May and 35.9% in November) and deep (32.8% in May and 38.4% in November) soil layers during the dry season and switched its main water source to surface layers (50.3% in July and 37.2% in September) during the wet season. Contrary to *P. orientalis*, *Quercus variabilis* mainly absorbed water from surface and middle soil layers during the dry season and changed its dominant water sources to the deep soil layer throughout the wet season; at same time, this species utilized water from natural springs in July and the middle soil layer in September. *V. negundo var. heterophylla* mostly utilized water from deep soil layers (38.7%) in May and transferred its main water source to surface (43.5%) and middle (33.1%) layers in July. This species primarily utilized water from surface (29.2%) and middle (30.8%) soil layers in September, and from middle (35.4%) and deep (27.8%) layers in November, similar to the findings of *P. orientalis* in this season. In contrast the above three plant species, *C. heterophylla Fisch* mainly absorbed water from surface and middle soil layers throughout the year, having very little reliance on water from deep soil layers. *P. orientalis* and *Q. variabilis* showed the opposite characteristics of water utilization, which suggests that these two species are suitable for a mixed forest vegetation when selecting plant species for afforestation. However, since the water sources of *P. orientalis* and *V. negundo var. heterophylla* were from similar soil depths, there may be potential competition for moisture between these two species. Our findings provide an indication as to which vegetation species are suitable to grow together when undertaking restoration in drought prone environments.

1. Introduction

Forest plays an important role in hydro-logical cycles and ecological functions in terrestrial ecosystem (Craigd et al., 2010; Yan et al., 2011; Jiang et al., 2013; Rowland et al., 2015). The area of artificial forest is the largest among all forest types in China, and the majority was widely distributed in the mountainous area due to the limitations of geographical conditions (Cheng et al., 2010). As one of the typical mountainous areas, the rocky mountainous area of North China also distributed large area of artificial forests. It was dominated by thin soils and high gravel concentration, and was frequently and severely impacted by seasonal drought. The rainfall in this area has an uneven distribution throughout the whole year, and result in this area experienced a long period of drought. The long period of deficiency of soil water caused by seasonal drought may be a key factor that limits vegetation growth and distribution (Zhang, 2011; Zhai et al., 2014). Because limited water input will intensify competition of water sources among species and affect the physiological activity of vegetation probably (Tezak, 1999). Nevertheless, the artificial forests, such as pure forest and mixed forest in this area was good to survive depend only on natural precipitation. It was suggested that vegetation within an ecosystem can vary their water source depending on water availability to maintain community coexistence and diversity (Schwinning et al., 2005; Saha and Miralles-Wilhelm, 2009; Kambatuku et al., 2013). Most vegetation was able to survive and live together, primarily owing to trees showed considerable plasticity in absorbing water sources according to the moisture, physiological characteristics and tree species allocation (Flanagan and Ehleringer, 1992; Kray et al., 2012; Zhou et al., 2015). Whereas, several tree species only uptake water from the deep or shallow soil layer, exhibited no changed of water source

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(Asbjornsen et al., 2008; Eggemeyer et al., 2009; Nie et al., 2011). A number of previous studies have mainly focused on conducting water source of vegetation community under conditions of plentiful rainfall (Schenk and Jackson, 2005; Yang et al., 2015), or single tree species in the arid area (Kray et al., 2012; Wu et al., 2016), or contrasting water use strategies in agroforestry system (Xi et al., 2013; Xiao and Huang, 2016), or the tree species with a thick soil layer (Xu et al., 2011; Jian et al., 2016). However, few studies focused on the water use patterns of the symbiotic of woody-shrub under a seasonal drought in the rocky mountainous area, which is characterized by thin soils and high gravel concentration. Moreover, seasonal drought will become more frequent and intense in some regions due to global climate change, which may lead to significant changes in the absorption depths and competitive relationship of plant water sources (IPCC, 2013). Thus, it is important to investigate how vegetation community uses water from different soil depths, to explore whether there was a water competition among the vegetation communities and to acquaint how they adapt to the fragile ecological environment.

The artificial mixed forests of *Platycladus orientalis–Quercus variabilis* are widely distributed in the mountainous area of North China, which have significant functions in ecological barrier of North China Plain. Therefore, acquainted the water use strategy and symbiotic mechanism of coexisting species in this region was significant implications for selection, allocation and later management of future artificial forest construction. To fill these gaps in our knowledge, we applied stable isotope techniques to investigate the absorption ratio of the vegetation community to each water source and using TDP to explore the water consumption of them. The objectives of this study are to (i) analyze the competitive interactions of the water utilization characteristics for two tree species (*Platycladus orientalis* and *Quercus variabilis*) and two undergrowth shrubs (*Vitex negundo L. var. heterophylla* and *Corylus heterophylla Fisch*), (ii) investigated the impacts of seasonal drought on water sources in this vegetation community. This study will help us acknowledge how vegetation adapts to the environment and advancing our knowledge of how vegetation communities survive competition during seasonal variations in limited water supply, as well as find the possibilities to ameliorate these changes through management or the recovery of artificial vegetation communities.

2. Materials and methods

2.1. Study site

Our study was conducted at the National Forest Ecosystem Research Station (40°03′N, 116°05′E), which is located in the mountainous area of Beijing. The study area, located 30 km from Beijing (Fig. 1), has an average altitude of 450 m and a warm temperate semi-humid monsoon climate. Each season has distinct characteristics in this region, with more rainfall in the summer (June to September) than in the other seasons. The average air temperature is 11.6 °C, with monthly means of − 19.6 °C in December and 27.6 °C in July; more than 10 °C of the effective accumulated temperature ranges from 3385–4210 °C in the course of a year. The annual mean rainfall is 660 mm with approximately 70–80% occurring in the wet season, especially in July and August, and the cumulative precipitation in other seasons was less than 30%. Mean annual evapotranspiration is approximately 1100 mm. The soil in the study region is thin with a depth of 80–100 cm. The soil types are mainly clay, which has higher soil humus contents in the surface layers and a higher density of gravel content in deep soil layers.

2.2. Vegetation species in the community

This study area, belonging to the typical Northern rocky mountainous area, has a mixed artificial forest vegetation of *Platycladus orientalis* and *Quercus variabilis* which was mainly planted by the local government in the early 1950s. *Vitex negundo L. var. heterophylla* and *Corylus heterophylla Fisch* are present under the stand. *Platycladus orientalis* is an evergreen coniferous tree that is widely distributed across China. This tree is the main afforestation tree species in the Beijing mountain area due to its strong resistance to cold and drought. *Quercus variabilis* is a deciduous broadleaf tree that has strong adaptability to climate and soil. This tree species is important in afforestation and ecological shelterbelt construction due to its well-developed taproot and lateral roots, and it has strong wind resistance. *V. negundo L. var. heterophylla* and *C. heterophylla Fisch* is sheepberry, which are mainly grown under forest woodland on the sunny slopes. In this community with an area of 400 m^2, there were 129 and 134 shrubs of *V. negundo var. heterophylla* and *C. heterophylla Fisch*, respectively. In comparison, there were 37*P. orientalis* and 43 *Q. variabilis* trees (Table 1). The average height of *P. orientalis* was 7.16 m with a mean tree diameter at breast height (DBH) of 7.60 cm, which was lower than the average height (9.18 m) and DBH (11.59 cm) of *Q. variabilis*.

2.3. Collection of soil, branch, precipitation and natural spring samples

Firstly, the basic meteorological parameters showed the information of seasonal drought in the study area. Secondly, analysis of the isotopic compositions of precipitation and the soil water content can provide more information of water sources, and show the impacts of seasonal drought on water sources. Thirdly, using the isotopic values of soil water and natural spring samples to calculate the contribution ratio of water sources for tree species during the growing season (May and November represent the dry season; July and September represent the wet season. May is in the transition from the dry season to the wet season; November is in the transition from the wet season to the dry season; July and September is in the wet season). Finally, contrasting the water sources of symbiotic of woody-shrub showed the competitive interactions between them and acquainted the impacts of seasonal drought on water sources in this vegetation community.

In the Beijing mountainous area, the deciduous tree species begin to grow leaves in the middle of April and shed their leaves in November, thus April to November is referred to as the growing season. To reflect the characteristics of water sources and use by plant communities for the whole growing season, all of the soil, branch, precipitation and natural spring samples were collected during May, July, September and November 2012. All samples were collected once a week during each month.

In the study plot, three mature sample trees of *P. orientalis* (according to their average height and DBH) were randomly selected for analysis. Non-green, ripe and suberized branches of 0.3–0.6 cm in diameter in the same direction and height from the ground were collected by scissor, and the sampling was repeated three times per trees. Three *Q. variabilis* trees were identified close to the studied *P. orientalis* trees and its branch samples were collected using the same method, and repeated three times at each tree. Under the canopy of the six trees, we chose three *V. negundo L. var. heterophylla* and three *C. heterophylla Fisch* sample shrubs and cut branch samples 0.5 cm from the base of the stem, and repeated three times at each tree. Samples were collected from each tree/shrub at each sampling period (once a week in each month) and all of the branch samples had their bark immediately removed before the samples were placed into the clean polyethylene bottles (50 ml), sealed with parafilm M®, frozen at –4°C to avoid evaporation fractionation, and then stored until isotopic analysis.

Soil samples were collected close to the tree/shrub sample locations using a soil auger at depths of 0–20 cm, 20–40 cm, 40–60 cm, 60–80 cm and 80–100 cm (below 80 cm was bedrock) in each sampling period, and repeated three times at each soil layer. Pebble gravel and litter were removed from the soil samples before they were divided into two parts: one part was immediately placed in clean polyethylene bottles (50 ml), sealed with Parafilm M® and stored in a refrigerator at –4°C for isotopic analysis, while the other part was sealed in a polythene bag and used to calculate soil water content by drying method (105 °C).

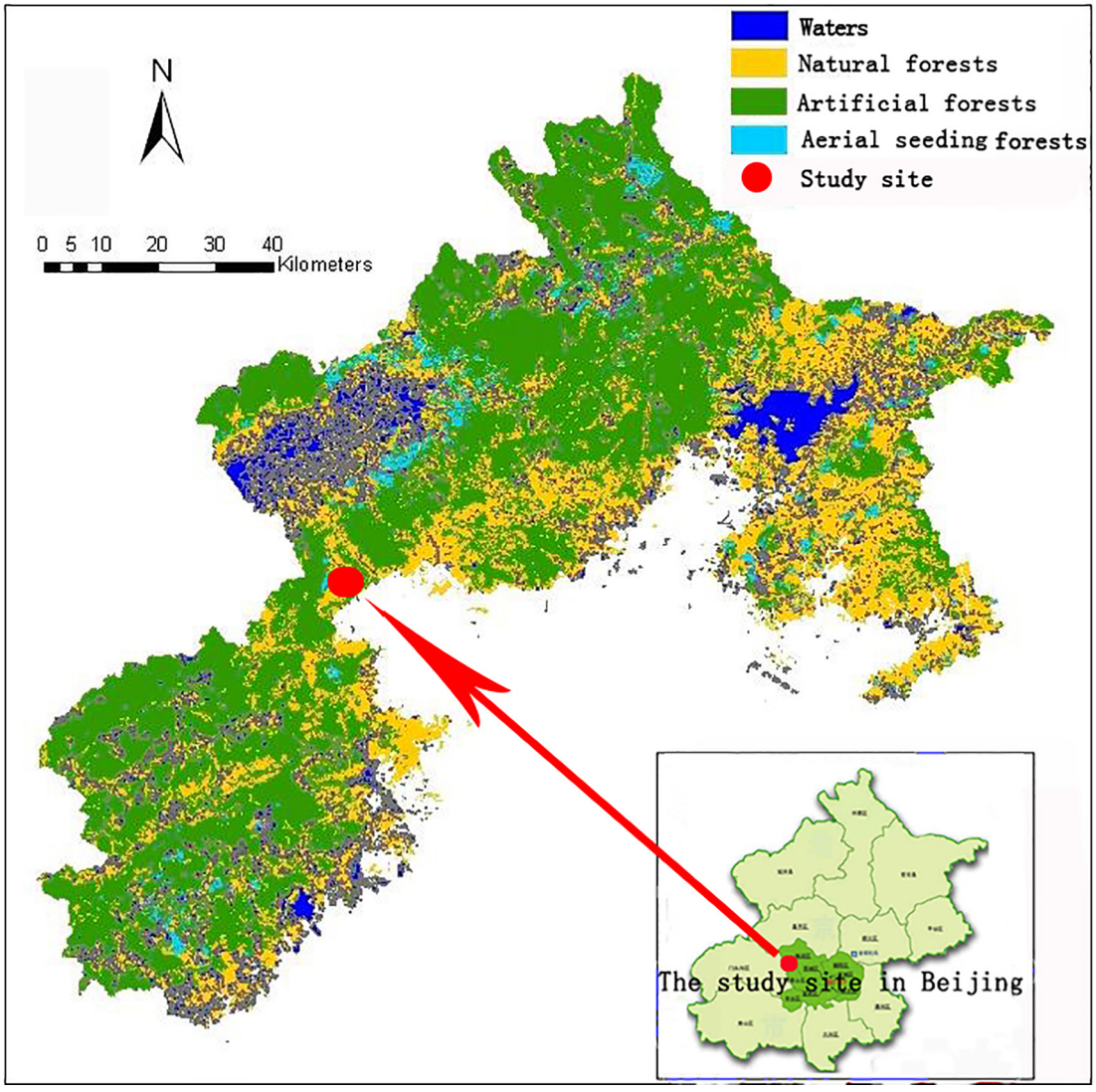

Fig. 1. Geographic location of the study area.

Table 1
Basic information of the vegetation species in the community.

Plot size/m	Land class	Vegetation species	Category	Number	Average height/m	DBH (Base diameter) /cm
20 × 20	Mixture plantation	Platycladus orientalis	Arbor	37	7.16 ± 1.53	7.60 ± 2.83
		Quercus variabilis	Arbor	43	9.18 ± 1.15	11.59 ± 3.91
		Vitex negundo var. heterophylla	Shrub	129	0.79 ± 0.16	1.87 ± 0.03
		Corylus heterophylla Fisch	Shrub	134	1.60 ± 0.28	1.59 ± 0.05

Natural spring was collected at Jinshan temple, located 1.3 km from the soil sampling point. Natural spring samples were collected in triplicate at each sampling interval using 50–ml plastic test tubes. The water samples were wrapped in Parafilm M® and stored in a frozen state to avoid evaporation fractionation, and then stored until isotopic analysis.

Rainfall samples were collected using a forest weather station which was located 1 km from the soil sampling point. Three iron collection buckets were used to collect precipitation samples with no surrounding barriers. A funnel containing a table tennis ball was placed at the top of each bucket to prevent isotope fractionation from evaporation. Rainfall samples were collected after the end of each rainfall event that was more than 2 mm. The collected samples were quickly transferred to clean polyethylene bottles (50 ml), sealed with Parafilm M®, and repeated three times, numbered and frozen.

2.4. Stable isotopic composition and water source analysis

All of the soil, branch, precipitation and natural spring samples were analyzed in the laboratory of eco hydrological processes and mechanisms, Beijing Forestry University. Soil and branch samples were restored to room temperature before water was extracted using a cryogenic vacuum distillation approach (West et al., 2006). The LGR DLI–100 was then used to measure hydrogen and oxygen isotopic values of the extracted water for plants and soil and to measure the water from the precipitation and natural spring samples. The accuracy of the instrument was ± 0.32‰ for δ^2H and ± 0.17‰ for ^{18}O. The values of ^2H and ^{18}O are expressed as $^2H/H$ and $^{18}O/^{16}O$ relative to Vienna Standard Mean Ocean Water (VSMOW) in ‰, respectively. The equation used for this analysis was:

$$\delta^2H/^{18}O(‰) = \frac{R_{sample} - R_{standard}}{R_{standard}} \times 1000$$

where, R represents the value of ($^2H/H$ or $^{18}O/^{16}O$) of the sample or the standard (VSMOW).

Water present in tree branches is potentially derived from water absorbed by the tree roots, thus, hydrogen and oxygen values in the branches can reflect information about root water sources (Jackson et al., 1999). According to the principle of isotopic mass conservation, the Iso-source model was used to calculate the contribution ratio of water sources for tree species (Phillips and Gregg, 2003). We compared the values of water content, hydrogen and oxygen isotopes in the soil layer and merged the soil layers with the same or similar isotopic values to form four water sources: surface soil layer (0–20 cm), middle soil layer (20–60 cm), deep soil layer (60–100 cm) and natural spring water.

2.5. Measurement of sap flow

The sap flow rate was measured using a commercially available thermal dissipation probes (Model TDP–10, Dynamax, TX, USA) based on the thermal diffusion principle. Six cylindrical probes, each 10 mm in length and 1.3 mm in diameter, were inserted 10 mm into the sapwood of tree bole-holes of four trees (two of *P. orientalis* and two of *Q. variabilis*). The sap flow data acquisition interval was 15 min from April to December. We choose the sap flow data at the sample collection time in our study. The equations for calculating the sap flow rate can be expressed as:

$$V_s = 0.0119K^{1.231}$$

$$K = (d_{Tm} - d_T)/d_T$$

where, V_s is the sap flow rate; K is the dimensionless constant; d_{Tm} is the maximum temperature throughout the day; and d_T is the instantaneous temperature.

2.6. Statistical analysis

Statistical analyses were performed utilizing the SPSS 16.0 program. Firstly, Two-way ANOVAs were used to analyze differences in the soil water content, δ^2H and $\delta^{18}O$ values (0–10, 10–20, 20–30, 30–40, 40–60, 60–80 and 80–100 cm, n = 36 for each soil stratum) with soil depths and seasons as factors. Then, one-way ANOVAs were used to test for differences in the sap flow rate among *Q. variabilis* and *P. orientalis* (n = 12), and the proportions of feasible water sources at each soil depth (0–20, 20–60, 60–100 and natural spring, n = 36 for each water source). The LSD method was used to compare the soil water content and proportions of feasible water sources when necessary. All data was tested for normal distribution and homogeneity of variance analysis, which meet the requirements of variance analysis.

3. Results

3.1. Precipitation and temperature variation characteristics

The study area is a typical seasonal drought area in North China, which has an average annual precipitation of 660 mm (Li et al., 2013). However, the yearly rainfall in 2012 was 745.2 mm, which was 12.90% greater than the annual average due to an extraordinary sixty–year storm on July 20th (Fig. 2). Precipitation during the wet season (June to September) was 583.4 mm, accounting for 78.3% of the annual precipitation, out of this, 146.8 mm was recorded on July 20th, which accounted for 19.7% of precipitation and 25.2% of the wet season precipitation. Precipitation in May and November (dry season) was 36.0 mm and 58.4 mm, respectively. Monthly rainfall initially increased with seasonal variation before the rainy season and precipitation in July was eight times greater than that recorded in May (36.0 mm). The average daily temperature showed an initial increase and then a decrease with monthly variation. The highest temperature (of 30.0 °C) was recorded on July 11th.

3.2. Variation in soil water content (SWC)

Soil water content (SWC) exhibited significant seasonal changes in the soil layers during the growing season (Fig. 3). The average SWC in July was 23.02%, which was significantly higher than that in May, September and November ($P < 0.05$). The average SWC was lowest in May (6.08%), and it was significantly lower than that in September. In May, the SWC of the 0–10 cm layer was significantly lower than those in other soil layers. In July, the SWC of the 0–10 cm layer was significantly higher than those in the other soil layers ($P < 0.05$), but there were no significant differences in the 20–30 cm, 30–40 cm and 40–60 cm layers ($P > 0.05$). The SWC of the 80–100 cm soil layer was significantly lower than those of the other soil layers. The variation characteristics of SWC in September were similar to those in July, other than those in November. The SWC of November recorded a decrease with an increase of soil depth across the whole profile, and the SWC of the 0–10 cm and 10–20 cm layers were significantly higher than those in the 20–30 cm, 30–40 cm and 40–60 cm soil layers ($P < 0.05$).

3.3. Soil water isotopic variation

The δ^2H and $\delta^{18}O$ values of soil water differed among the soil depths during the growing season (Fig. 4). The isotopic composition of soil water decreased along with the soil depth in May, July and September, however, the hydrogen and oxygen isotope values showed an initial increase in the 0–20 cm soil layer before decreasing throughout the rest of the soil profile in November. In the growing season, the δ^2H and $\delta^{18}O$ composition in the surface (0–20 cm) soil water were more enriched than in the other soil layers. The δ^2H and $\delta^{18}O$ values in May were greater than those in the other months. The δ^2H and $\delta^{18}O$ values of soil water in July were typically more depleted than those in May, September and November. There were no significant isotopic differences in the 80–100 cm soil layer during the growing season ($P > 0.05$). (See Fig. 5).

3.4. Isotopic characteristics of rainfall, soil water, natural spring and stem water

Rainfall samples were collected and δ^2H and $\delta^{18}O$ values were analyzed to obtain the local meteoric water line (LMWL: $\delta^2H = 6.64\delta^{18}O - 4.61$ ($R^2 = 0.94$, n = 33, $P < 0.05$) in 2012. The slope and intercept of the LMWL were both less than the global meteoric water line (GMWL: $\delta^2H = 8.17\delta^{18}O + 10.56$, Craig, 1961), indicating that a certain degree of evaporation fractionation occurred. The isotopic values of precipitation varied significantly. The δ^2H ranged from –105.23 ‰ to –13.96 ‰, with an average of –59.97‰, and $\delta^{18}O$ ranged from –14.43 ‰ to –0.51 ‰, with an average of –8.33 ‰. Isotopic values for soil water were –90.25 ‰ to –33.26 ‰ for δ^2H, with an average value of –72.21 ‰, and –11.50 ‰ to –1.41 ‰ for $\delta^{18}O$, with an average value of –8.65 ‰. The variation in the range of the isotopic values in soil water was less than that for rainfall water. The soil water values were also below those of the LMWL, suggesting that evaporative enrichment occurred in our soil water collection. The results for isotopic composition in stem water were also below the LMWL values and similar to the soil water values, indicating that stem water was predominantly obtained from different soil layers. The LMWL results also indicated that the natural spring water was potentially transformed from precipitation.

3.5. Stem sap flow rate characteristics

The stem sap flow rate results showed that there was a noticeable

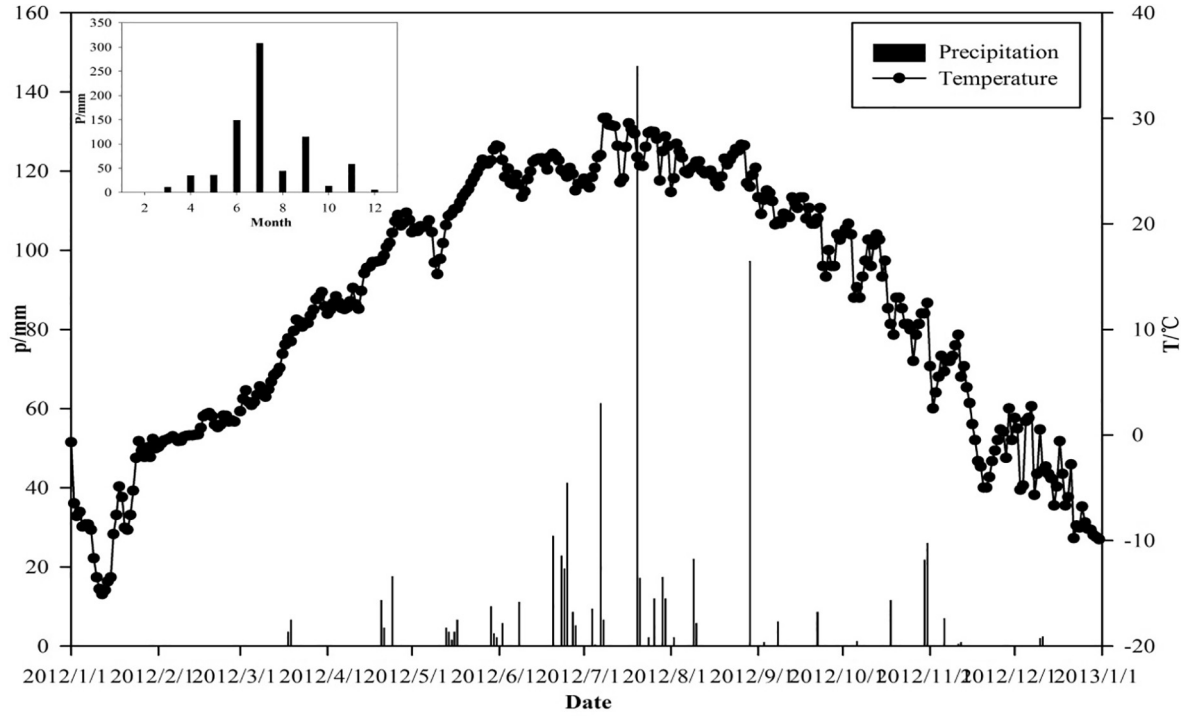

Fig. 2. The variation characteristics of precipitation and temperature. P indicates precipitation; T indicates temperature. The subgraph shows monthly mean precipitation.

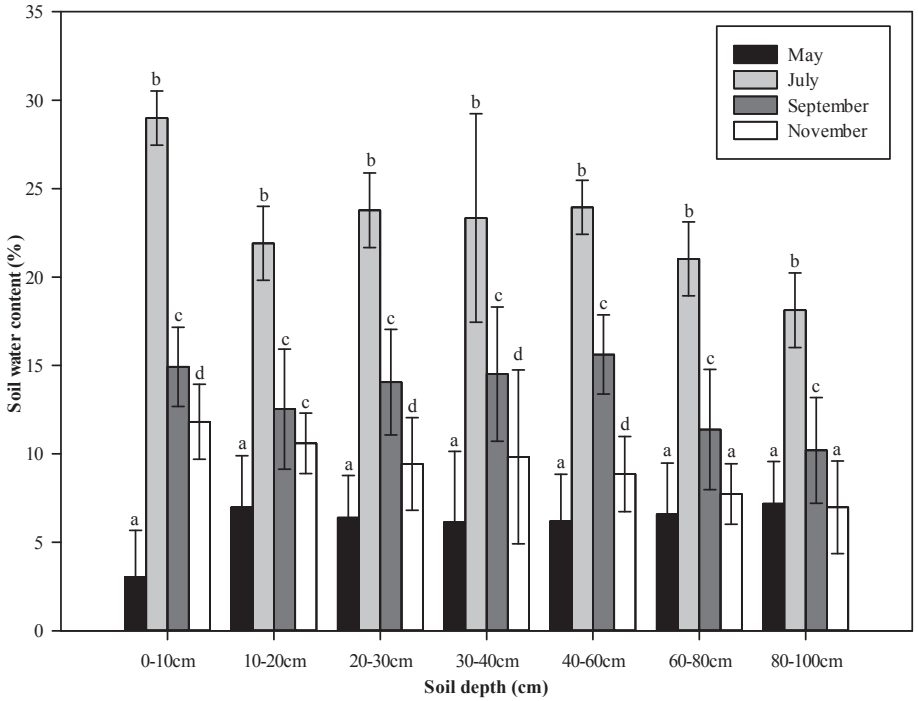

Fig. 3. Mean (± S.D.) soil water content changes in the study area. The different letters indicate significant differences in the soil water content among the different season ($\alpha = 0.05$).

difference between the two tree species during the growing season (Fig. 6). Overall, the average sap flow rates of *Q. variabilis* and *P. orientalis* in July were significantly higher than those for the other months ($P < 0.05$) (it attained its maximum during this month) and the average value of sap flow rate in November was significantly lower than that in the other months ($P < 0.05$). The peak value of the sap flow rate of *Q. variabilis* was greater than that of *P. orientalis* in May and July, and lower than *P. orientalis* in September ($P < 0.05$). There was no significant difference in the peak value of the sap flow rate between *Q. variabilis* and *P. orientalis* in November.

3.6. Variation of plant water-source utilization

The Iso-Source mixture model was used to calculate the ratio of

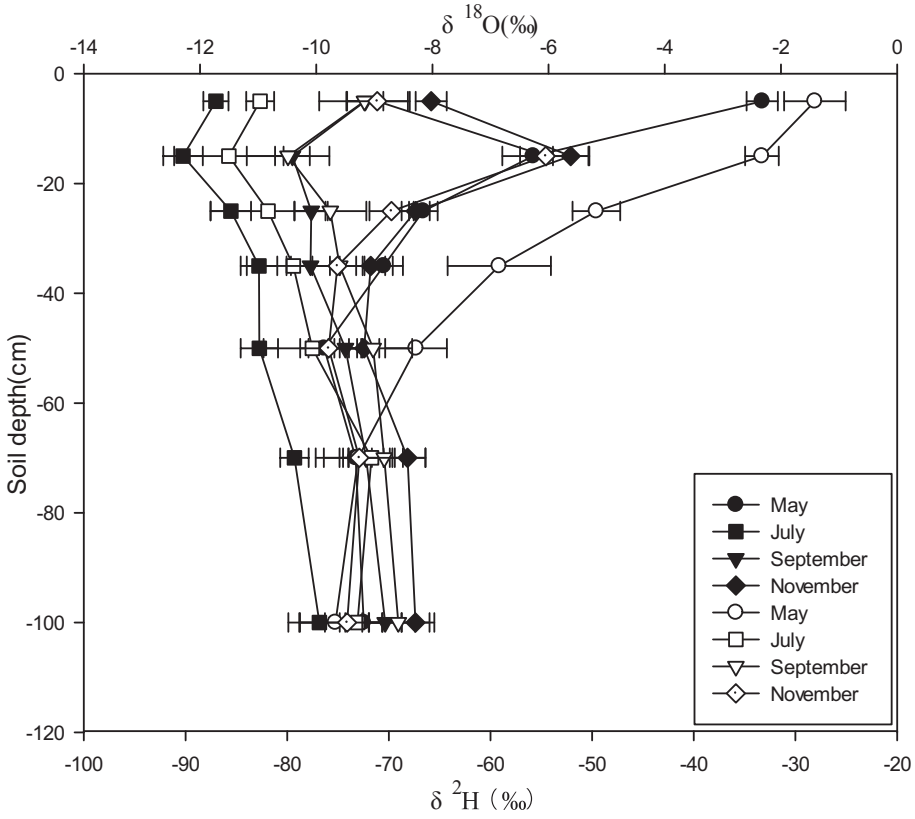

Fig. 4. Variation characteristics of mean (± S.D.) δ^2H and $\delta^{18}O$ values in the soil profile during the growing season. The open and closed symbols were ^2H and $\delta^{18}O$ respectively.

water sources by vegetation type. The results showed that the water sources of the vegetation varied seasonally (Table 2). *Platycladus orientalis* absorbed water from the middle (31.5% and 35.9%, respectively) and deep (32.8% and 38.4%, respectively) soil layers in May and November, which was more than that from the surface soil layer or from the natural spring. In July and September, surface water (50.3% and 37.2%, respectively) absorption by *P. orientalis* was significantly higher than that from the natural spring or from middle or deep soil

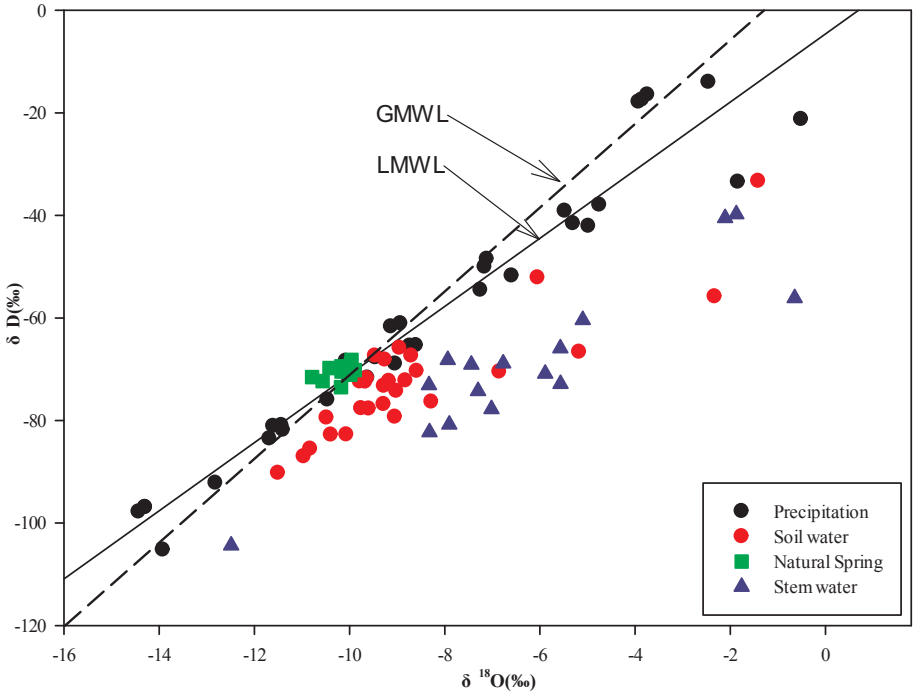

Fig. 5. The relationship between isotopic values in precipitation, soil water, natural spring and stem water. The local meteoric water line (LMWL) in 2012 was $\delta^2H = 6.64\delta^{18}O - 4.61$ ($R^2 = 0.94$, n = 33). The global meteoric water line (GMWL) was $\delta^2H = 8.17\delta^{18}O + 10.56$ (Craig, 1961).

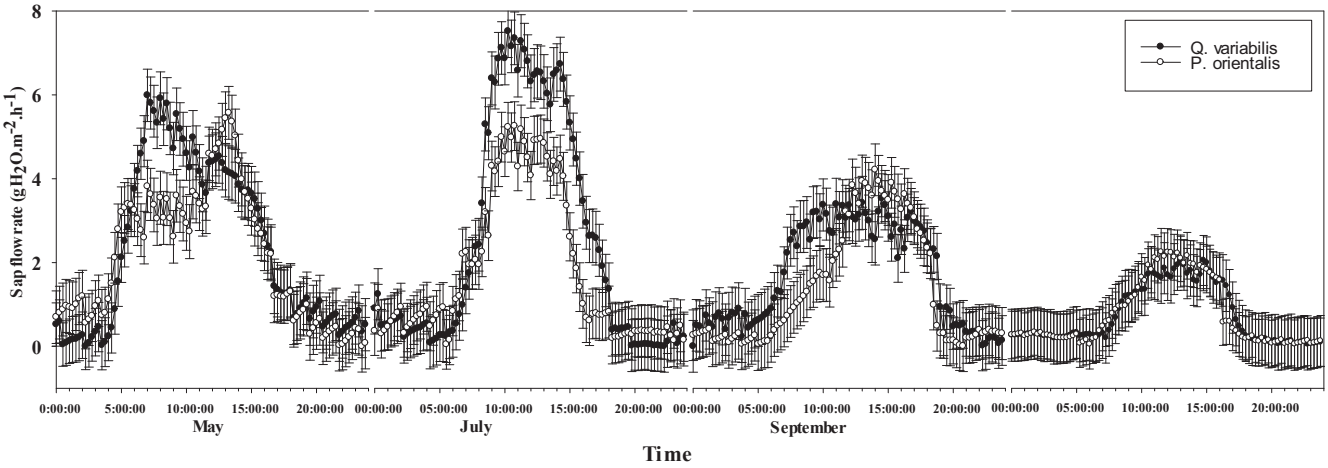

Fig. 6. The variation in the mean (± S.D.) stem sap flow of the two tree species during the growing season.

Table 2
Mean (± S.D.) proportions of feasible water sources for the four species during the growing season.

Month	Water source	*P. orientalis* (%)	*Q. variabilis* (%)	*V. negundo var. heterophylla* (%)	*C. heterophylla Fisch* (%)
May	Soil (0–20 cm)	20.2 ± 2.9 a	40.0 ± 3.6 a	21.1 ± 2.5 a	34.3 ± 3.1 a
	Soil (20–60 cm)	31.5 ± 2.6b	31.6 ± 2.3b	17.4 ± 2.2 a	37.0 ± 2.5 a
	Soil (60–100 cm)	32.8 ± 3.8b	18.2 ± 2.6c	43.7 ± 2.4b	19.5 ± 1.9b
	Natural Spring	15.5 ± 4.0c	10.2 ± 4.0 d	17.8 ± 2.8 a	9.2 ± 1.3c
July	Soil (0–20 cm)	50.3 ± 2.8 a	2.7 ± 2.5 a	43.5 ± 2.2 a	36.8 ± 3.3 a
	Soil (20–60 cm)	18.0 ± 2.9b	12.8 ± 2.4b	33.1 ± 2.9b	30.4 ± 2.7b
	Soil (60–100 cm)	16.5 ± 1.5b	46.5 ± 2.2c	13.2 ± 2.9c	27.7 ± 2.4b
	Natural Spring	15.2 ± 2.0b	38.0 ± 1.5 d	10.2 ± 2.6c	5.1 ± 1.7c
September	Soil (0–20 cm)	37.2 ± 4.9 a	12.1 ± 2.0 a	29.2 ± 2.3 a	32.2 ± 2.0 a
	Soil (20–60 cm)	22.4 ± 3.5b	32.7 ± 3.1b	30.8 ± 2.4 a	35.9 ± 2.6 a
	Soil (60–100 cm)	20.6 ± 2.9b	37.4 ± 1.9b	23.5 ± 3.0b	23.2 ± 3.2b
	Natural Spring	19.8 ± 2.2b	17.8 ± 2.0c	16.5 ± 2.1c	8.7 ± 1.8c
November	Soil (0–20 cm)	13.2 ± 2.1 a	31.6 ± 1.4 a	22.2 ± 2.1 a	32.0 ± 3.1 a
	Soil (20–60 cm)	35.9 ± 1.7b	30.6 ± 2.1 a	35.4 ± 1.7b	34.5 ± 2.2 a
	Soil (60–100 cm)	38.4 ± 2.6b	25.8 ± 2.7b	27.8 ± 2.0c	23.7 ± 2.9b
	Natural Spring	12.5 ± 4.3 a	12.0 ± 1.1c	14.6 ± 3.8 d	9.8 ± 1.2c

Water source proportions were calculated using the Iso-Source mixture model. Different letters indicate significant differences in soil water proportions among the different water sources.

layers. *Quercus variabilis* mainly absorbed water from the surface (40.0% and 31.6%, respectively) and middle (31.6% and 30.6%) soil layers during the dry season and obtained water from the deep soil layer throughout the wet season, and it utilized water from natural springs (38.0%) in July and the middle soil layer (32.7%) in September. The water use patterns of *V. negundo var. heterophylla,* although similar to *P. orientalis* during the growing season, differed in the proportion of water sources. This species primarily utilized deep soil water (43.7%) in May and transferred its water sources to surface (43.5% and 29.2%, respectively) and middle soil layers (33.1% and 30.8%, respectively) in July and September. In November, it absorbed water from the middle and deep soil layers. *C. heterophylla Fisch* mostly absorbed water from surface (34.3%, 36.8% and 32.2%) and middle (37.0%, 30.4% and 35.9%) soil layers in May, July and September, respectively, and utilized deep soil water (33.7%) in November; it rarely utilized natural spring water during the growing season.

4. Discussion

4.1. Water content and isotopic characteristics of potential water sources

Soil water and groundwater, two of the most important water sources for vegetation, originally derived from precipitation (Alessio et al., 2004). The seasonal distribution characteristics of precipitation have direct impacts on SWC and isotopic values (Dawson and Ehleringer, 1991). In our study, the values of soil water and rainfalls and their isotopic compositions showed obvious changes with changing seasons. The slope and intercept of the LMWL ($\delta^2H = 6.64\ \delta^{18}O - 4.61$) were less than that of the GMWL ($\delta^2H = 8.17\delta^{18}O + 10.56$), and the great variation in δ^2H and $\delta^{18}O$ values of precipitation indicated that water vapor had different degrees of fractionation in the process of precipitation due to strong evaporation of water vapor transported between sea and land. In our study, the number of days in the dry season (approximately 270 days) was far more than that in the rainy season, which could lead to evaporative enrichment in isotope values in precipitation. Wen et al. (2010) also found that the composition of hydrogen and oxygen isotopes in precipitation around Beijing had a distinct seasonal variation. The degree of fractionation of δ^2H and $\delta^{18}O$ were significantly different between the dry and the wet seasons (Lee and Kim, 2007). Generally, more isotopic composition enrichment occurred in the dry season than in the wet season due to stronger evaporation of water vapor in the dry season (Asano et al., 2002). It was also identified that the isotopic values of soil water were in a state of constant change after precipitation due to soil evaporation, change in SWC and soil properties (Allison, 1982; Gazis and Feng, 2004; Braud et al., 2009). The δ^2H and $\delta^{18}O$ values in soil water were below those of the LMWL, indicating an isotopic enrichment in the rainfall infiltration process. On the whole, the δ^2H and $\delta^{18}O$ isotopic compositions of soil water in July were more negative than those in May, September and November. This was due to the direct impact of precipitation on soil

water because precipitation had a more dilute isotopic value in the dry season, and this has also been found in other regions (Ingraham et al., 1991; Jones et al., 2000). With increasing soil depth, the δ^2H and $\delta^{18}O$ values became more negative during the growing season. The range of isotopic values of water in the surface soil was larger than that in the deep layers, especially in May when the isotopic composition in the surface layer changed drastically. This could be attributed to the significant influence of precipitation recharge and evaporation. Hydrogen and oxygen isotope compositions in the middle and deep soil layers had less changes compared with the surface soil layer due to weakened evaporation. Our findings are in strong agreement with the results of Wu et al. (2016) who identified that soil water in the surface soil layer had enriched isotopic values with low SWC and had relative negative isotopic values in the deep soil layer. Gazis and Feng (2004) demonstrated that a strong evaporation effect generally occurred in surface soil layers, and faded with increasing soil depth. Cheng et al. (2006) also reported that surface soil water was noticeably affected by evaporation fractionation and the evaporation effect gradually weakened with increasing soil depth. The isotope values of natural spring water were distributed on the LMWL and were shown to be relatively stable during the growing season. Since the natural spring water was located at deep depths, it was not possibly affected by external environmental changes. Our results are consistent with those of Perrin et al. (2003) and White (2002).

4.2. Analysis of water use characteristics

The four species analyzed in our investigation have the same potential water sources, however, the results showed that they utilized proportions of water sources differently. *P. orientalis* and *Q. variabilis* showed opposite characteristics of water utilization. *Platycladus orientalis* mainly absorbed water from the middle and deep soil layers in the dry season and transferred its water source to the surface soil layer in the wet season. In addition, *P. orientalis* did not access water from natural springs in different seasons. In contrast, *Q. variabilis* predominantly obtained water from the surface and middle soil layers during the dry season and switched its water source to middle, deep soil layers and natural springs in the wet season. The water use patterns of these two tree species may be related to their root distribution and physiological characteristics (Ward et al., 2013). According to our survey findings, *P. orientalis* has an extensive network of lateral roots in surface soil layers and *Q. variabilis* has developed a taproot system (data not shown), these findings are consistent with those of Ji et al. (2012) and Liu et al. (2016). In May and November when SWC was low, especially in the surface soil layer, to maintain transpiration and normal physiological activity, *P. orientalis* mainly used water from the relatively stable middle and deep soil layers. When the surface soil moisture was sufficient, it predominantly sourced water from the surface soil layer via lateral roots that contained numerous root hairs. The phenomenon of water use patterns due to changing environmental conditions is called “plasticity dimorphic root system” (Liu et al., 2014). The results are slightly different from previous studies that demonstrated that *P. orientalis* mainly uptakes water from natural springs in April (dry season) and switched its water sources to the surface soil layer in July (wet season) (Liu et al., 2017). This difference in water sources of *P. orientalis* may be attributed to water conditions. Due to less rainfall input, the average SWC of the profile in April (average SWC was 2.17 ± 0.25) was relatively lower than that in May (average was SWC 6.08 ± 1.29), forcing *P. orientalis* to go deeper and mostly utilize natural springs. Previous studies and the current study confirmed that *P. orientalis* prefers to use shallower soil water with the increase of soil moisture. Vegetation seldom absorbs water from a single depth during the growing season, they generally switch their water source in response to variations in SWC and environmental conditions (Asbjornsen et al., 2008). Liu et al. (2014) also reported that the tree species with a shallow root system generally grabbed surface water easily when the SWC was adequate. The ecological plasticity caused plants to absorb water from deep soil layers when SWC in the shallow layer was limited (West et al., 2008; Li et al., 2006). When the SWC of each soil layer was low (May and November), *Q. variabilis* utilized the water of shallow and middle soil layers water to reduce the energy consumption of transporting moisture over a the long distance (Schenk and Jackson, 2002). However, a response has occurred in *Q. variabilis* when the SWC of each soil layer was high (July and September). *Quercus variabilis* accessed water in the natural spring, middle and deep soil layers using its developed taproot system. This water was not easily affected by evaporation which enabled a relatively stable moisture content to be maintained. Liu et al. (2017) also reported that *Q. variabilis* preferred to utilize water from deep soil layers with the increase of soil moisture. An adequate and stable water supply from deep soil layers could satisfy a large proportion of transpiration consumption by *Q. variabilis* (Asbjornsen et al., 2007; Liu et al., 2017). Plants generally adapt to changing habitats by changing their morphological or physiological characteristics (Nippert and Knapp, 2007a). In addition, the transpiration rate of *Q. variabilis* (broadleaf, deciduous) was larger than that of *P. orientalis* (needle leaf, evergreen). The different life forms of the two species resulted in different water use strategies. The water use patterns of *Q. variabilis* indicated that it preferred to utilize deep soil water, and it obtained enough deeper soil water during the dry season to ensure sustainability during this period. However, *P. orientalis* readily absorbed accessible water in the surface soil layer. *Platycladus orientalis* and *Q. variabilis* exhibited greater ecological plasticity in response to changes in water availability by altering root activity and they showed a positive adaptability to the changing environment.

The utilization ratio of water sources of *V. negundo var. heterophylla* was similar to *P. orientalis*. *V. negundo var. heterophylla* mainly absorbed water from deep soil layers in May and switched its water source to surface and middle soil layers in July and November. *V. negundo var. heterophylla* has a root system comprised of roots with a 1 mm diameter widely distributed in the 60 cm soil layer, composing the greatest root density in at this depth (Alam and Gomes, 2003). Therefore, this species will uptake water from this soil layer (middle and deep soil layer) during the growing season. Unlike *V. negundo var. heterophylla*, which has plasticity in its water-use patterns, *C. heterophylla Fisch* mainly absorbed water from surface and middle soil layers; only a small amount of water was obtained from deep soil layers and there was almost no utilization of natural spring water during the growing season. The water source of *C. heterophylla Fisch* may depend on the distribution of its root system which was largely concentrated in the 0–40 cm soil layer (Li, 2013). In general, shrubs will obtain water from the surface soil layer if there is enough surface moisture to satisfy growth and transpiration requirements (Wu et al., 2016). To adapt to the dry season, *V. negundo var. heterophylla* mainly absorbed water from the deep soil layers when surface water was difficult to obtain. This species could adjust the depth of absorbed water according to the different soil moisture conditions, indicating that *V. negundo var. heterophylla* may have a higher drought tolerance in response to water shortage during the dry season in seasonal drought areas than *C. heterophylla Fisch*. The majority of previous studies demonstrated that deep-rooted shrubs switched their water sources as soil moisture varied (Asbjornsen et al., 2008; Dai et al., 2014; Wu et al., 2016). Although a number of shrub species have ecological plasticity in root functions, most absorb surface soil water without changing the depth of water absorption (Nippert and Knapp 2007b; Asbjornsen et al., 2008). In general, the changing water use pattern of vegetation in a community is not only beneficial for adaptation to the drought environment but also reduces water competition with other species.

5. Conclusions

In our study, we used stable isotope techniques to determine the impacts of seasonal drought on water sources of vegetation community

during the growing season in a rocky mountainous area in Beijing, China. Iso-Source outputs suggested that the *P. orientalis* and *Q. variabilis* showed the opposite characteristics of water utilization. Meanwhile, the utilization ratio of water sources of *V. negundo var. heterophylla* was similar to *P. orientalis*, but quite different from *Q. variabilis*. The *P. orientalis* and *V. negundo var. heterophylla* tended to utilize surface soil water as the soil water conditions improved, conversely, the *Q. variabilis* prefer to utilize water from natural springs and the deep soil layer with the increase of soil moisture. However, *C. heterophylla Fisch* did not have a flexible change of water source. It mainly absorbed water from surface and middle soil layers and sourced a small amount of water from the deep soil layer. Our findings suggested that the *P. orientalis* and *V. negundo var. heterophylla* can be considered to be used together in humid areas with abundant rainfall, but may result in an increase in competition for moisture in arid or semiarid areas. The *P. orientalis* and *Q. variabilis* could be suitable for a mixed forest when selecting tree species for afforestation. *C. heterophylla Fisch* was suitable with plants that were inclined to utilize deep water or groundwater in the whole growing season. Further study considering plant transpiration and hydraulic redistribution (HR) of plant roots, as well as changes in external environmental conditions is required to better understand water uptake patterns among species and forest communities.

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References

Alam, M.I., Gomes, A., 2003. Snake venom neutralization by Indian medicinal plants (*Vitex Negundo* and *Emblica Officinalis*) root extracts. J. Ethnopharmacol. 86, 75–80.
Alessio, G.A., Lillis, M., Brugnoli, E., Lauteri, M., 2004. Water sources and water-use efficiency in Mediterranean coastal dune vegetation. Plant Biol. (Stuttgart). 6, 350–357.
Allison, G., 1982. The relationship between ^{18}O and deuterium in water in sand columns undergoing evaporation. J. Hydrol. 55, 163–169.
Asano, Y., Uchida, T., Ohte, N., 2002. Residence times and flow paths of water in steep unchannelled catchments, tanakami, Japan. J. Hydrol. 261, 173–192.
Asbjornsen, H., Mora, G., Helmers, M.J., 2007. Variation in water uptake dynamics among contrasting agricultural and native plant communities in the midwestern U.S. Agric. Ecosyst. Environ. 121, 343–356.
Asbjornsen, H., Shepherd, G., Helmers, M., Mora, G., 2008. Seasonal patterns in depth of water uptake under contrasting annual and perennial systems in the corn belt region of the midwestern U.S. Plant Soil 308, 69–92.
Braud, I., Biron, P., Bariac, T., Richard, P., Canale, L., Gaudet, J.P., 2009. Isotopic composition of bare soil evaporated water vapor. part i: rubic iv experimental setup and results. J. Hydrol. 369 (1–2), 1–16.
Cheng, S., Xu, Z., Su, Y., et al., 2010. Spatial and temporal flows of China's forest resources: Development of a framework for evaluating resource efficiency. Ecol. Econ. 69 (7), 1405–1415.
Cheng, X.L., An, S.Q, Li, B., Chen, J.Q., Lin, G.H., Liu, Y.H., Luo, Y.Q., Liu, S.R., 2006. Summer rain pulse size and rainwater uptake by three dominant desert plants in a decertified grassland ecosystem in northwestern China. Plant Ecol. l184, 1–12.
Craigd, A., Alisonk, M., Haroun, C., et al., 2010. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. For. Ecol. Manage. 259, 660–684.
Craig, H., 1961. Isotopic variations in meteoric waters. Science 133, 1702–1703.
Dai, Y., Zheng, X.J., Tang, L.S., Li, Y., 2014. Stable oxygen isotopes reveal distinct water use patterns of two Haloxylon species in the Gurbantonggut Desert. Plant Soil. 12, 1–15.
Dawson, T.E., Ehleringer, J.R., 1991. Streamside trees that do not use stream water. Nature 350, 335–337.
Eggemeyer, K.D., Awada, T., Harvey, F.E., Wedin, D.A., Zhou, X.H., Zanner, C.W., 2009. Seasonal changes in depth of water uptake for encroaching trees Junipe-rus virginiana and Pinus ponderosa and two dominant C_4 grasses in a semiaridgrassland. Tree Physiol. 29 (2), 157–169.
Flanagan, L.B., Ehleringer, J.R., 1992. Differential uptake of summer precipitation among co-occurring trees and shrubs in a pinyon-juniper woodland. Plant, Cell Environ. 15, 831–836.
Gazis, C., Feng, X., 2004. A stable isotope study of soil water: evidence for mixing and preferential flow paths. Geoderma 119, 97–111.
Ingraham, N.L., Lyles, B.F., Jacobson, R.L., Hess, J.W., 1991. Stable isotopic study of precipitation and spring discharge in southern Nevada. J. Hydrol. 125, 243–258.
IPCC, 2013. Climate change 2013: the physical science basis. In: Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panelon Climate Change. Cambridge University Press, Cambridge, United Kingdomand New York, NY, USA.
Jackson, P.C., Meinzer, F.C., Bustamante, M., 1999. Partitioning of soil water among tree species in a Brazilian Cerrado ecosystem. Tree Physiol. 19, 717–724.
Ji, J., Kokutse, N., Genet, M., Fourcaud, T., Zhang, Z., 2012. Effect of spatial variation of tree root characteristics on slope stability. a case study on black locust (*Robinia pseudoacacia*) and arborvitae (*Platycladus orientalis*) stands on the loess plateau, china. Catena 92, 139–154.
Jian, S., Zhang, X., Wu, Z., et al., 2016. Water use pattern of Pinus tabulaeformis in the semiarid region of Loess Plateau, China. Forest Syst. 25 (3), 077–084.
Jiang, L.N., Lu, Q., Yang, W.B., et al., 2013. The promoting effect of vegetation recovery after the establishment of poplar fixing sand forest belts in the Horqin sandy land of Northeast China. J. Food Agric. Environ. 11 (3), 2510–2515.
Jones, I.C., Banner, J.L., Humphrey, J.D., 2000. Estimating recharge in a tropical karst aquifer. Water Resour. Res. 36, 1289–1299.
Kambatuku, J.R., Cramer, M.D., Ward, D., 2013. Overlap in soil water sources of savannawoody seedlings and grasses. Ecohydrology 6, 464–473.
Kray, J.A., Cooper, D.J., Sanderson, J.S., 2012. Groundwater use by native plants in response to changes in precipitation in an intermountain basin. J. Arid Environ. 83, 25–34.
Lee, K.S., Kim, Y., 2007. Determining the seasonality of groundwater recharge using water isotopes: a case study from the upper North Han River basin, Korea. Environ. Geol. 52, 853–859.
Li, M., Xia, J., Chen, Z., Meng, D., Xu, C., 2013. Variation analysis of precipitation during past 286 years in Beijing area, china, using non-parametric test and wavelet analysis. Hydrol. Process. 27, 2934–2943.
Li, Q., 2013. *Corylus heterophylla Fisch* characteristics and cultivation situation in Qapqal County. Mod Agric Sci Technol. 05, 140–143 (in Chinese).
Li, S.G., Tsujimura, M., Sugimoto, A., et al., 2006. Seasonal variation in oxygen isotope composition of waters for a montane larch forest in Mongolia. Trees 20, 122–130.
Liu, J., Bloomberg, M., Li, G., Liu, Y., 2016. Effects of copper root pruning and radicle pruning on first-season field growth and nutrient status of Chinese cork oak seedlings. New Forest. 47, 715–729.
Liu, W., Wang, P., Li, J., Liu, W., Li, H., 2014. Plasticity of source water acquisition in epiphytic transitional and terrestrial growth phases of Ficus tinctoria. Ecohydrology 7, 1524–1533.
Liu, Z., Yu, X., Jia, G., Jia, J., Lou, Y., Lu, W., 2017. Contrasting water sources of evergreen and deciduous tree species in rocky mountain area of Beijing, China. Catena 150, 108–115.
Nie, Y.P., Chen, H.S., Wang, K.L., Tan, W., Deng, P.Y., Yang, J., 2011. Seasonal water use patterns of woody species growing on the continuous dolostone outcropsand nearby thin soils in subtropical China. Plant Soil. 341, 399–412.
Nippert, J., Knapp, A., 2007a. Soil water partitioning contributes to species coexistence in tallgrass prairie. Oikos 116, 1017–1029.
Nippert, J.B., Knapp, A.K., 2007b. Linking water uptake with rooting patterns in grassland species. Oecologia 153, 261–272.
Perrin, J., Jeannin, P.Y., Zwahlen, F., 2003. Epikarst storage in a karst aquifer: a conceptual model based on isotopic data, Milandre test site, Switzerland. J. Hydrol. 279, 106–124.
Phillips, D.L., Gregg, J.W., 2003. Source partitioning using stable isotopes: coping with too many sources. Oecologia 136, 261–269.
Rowland, L., Da, C.A., Galbraith, D.R., et al., 2015. Death from drought in tropical forests is triggered by hydraulics not carbon starvation. Nature 528, 119–122.
Saha, A.K., Miralles-Wilhelm, F., 2009. Linking water sources with foliar nutrient status in upland plant communities in the Everglades National Park, USA. Ecohydrology. 2, 42–54.
Schenk, H.J., Jackson, R.B., 2002. The global biogeography of roots. Ecol. Monogr. 72, 311–328.
Schenk, H.J., Jackson, R.B., 2005. Mapping the global distribution of deep roots inrelation to climate and soil characteristics. Geoderma 126 (1), 129–140.
Schwinning, S., Starr, B.I., Ehleringer, J.R., 2005. Summer and winter drought in a cold desert ecosystem (Colorado Plateau) part I: Effects on soil water and plant water uptake. J. Arid Environ. 60, 547–566.
Tezak, E.P., 1999. Competitive differences between newly emerged off spring of captive-reared and wild coho salmon. Trans. Am. Fish. Soc. 128, 832–839.
Ward, D., Wiegand, K., Getzin, S., 2013. Walter's two-layer hypothesis revisited: back to the roots!. Oecologia 172, 617–630.
Wen, X., Zhang, S., Sun, X., 2010. Water vapor and precipitation isotope ratios in Beijing. J. Geophys. Res. 115, 133–134.
West, A.G., Patrickson, S.J., Ehleringer, J.R., 2006. Water extraction times for plant and soil materials used in stable isotope analysis. Rapid Commun. Mass Spectrom. 20, 1317–1321.
West, A.G., Sperry, J.S., Bush, S.E., Ehleringer, J.R., 2008. Transpiration and hydraulic strategies in a pinon-juniper woodland. Ecol. Appl. 18, 911–927.
White, W.B., 2002. Karst hydrology: recent developments and open questions. Environ. Geol. 65, 85–110.
Wu, H.W., Li, X.Y., Jiang, Z.Y., Chen, H.Y., Zhang, C.C., Xiao, X., 2016. Contrasting water use pattern of introduced and native plants in an alpine desert ecosystem, northeast Qinghai–tibet plateau, China. Sci. Total Environ. 542, 182–191.
Xi, B., Wang, Y., Jia, L., Bloomberg, M., Li, G., Di, N., 2013. Characteristics of fine root

system and water uptake in a triploid populus tomentosa, plantation in the north china plain: implications for irrigation water management. Agric. Water Manag. 117 (1), 83–92.
Xiao, Q., Huang, M., 2016. Fine root distributions of shelterbelt trees and their water sources in an oasis of arid northwestern china. J. Arid Environ. 130 (130), 30–39.
Xu, B.C., Xu, W.Z., Huang, J., et al., 2011. Biomass allocation, relative competitive ability and water use efficiency of two dominant species in semiarid Loess Plateau under water stress. Plant Sci. Int. J. Exp. Plant Biol. 181 (6), 644–651.
Yan, Q.L., Zhu, J.J., Hu, Z.B., Sun, O.J., 2011. Environmental impacts of the shelter forests in horqin sandy land, northeast china. J. Environ. Qual. 40 (3), 815–824.
Yang, B., Wen, X., Sun, X., 2015. Seasonal variations in depth of water uptake for a subtropical coniferous plantation subjected to drought in an east asian monsoon region. Agric. For. Meteorol. 201, 218–228.
Zhai, Y., Guo, Y., Zhou, J., Guo, N., Wang, J., Teng, Y., 2014. The spatio-temporal variability of annual precipitation and its local impact factors during 1724–2010 in Beijing, China. Hydrol. Process. 28 (4), 2192–2201.
Zhang, Z., 2011. Factors affecting soil erosion in Beijing mountain forestlands. Afr. J. Biotechnol. 10, 17134–17141.
Zhou, T., Zhao, C., Yongxiang, Y.U., Guilin, W.U., Wang, L., 2015. Study on the water source of populus euphratica seedling and tamarix ramosissimaseedling based on stable hydrogen and oxygen isotope technology. J. Soil Water Conserv. 29 (04), 241–246.